

Episodic mass loss in binary evolution to the Wolf-Rayet phase: Keck and *HST* proper motions of RY Scuti’s nebula^{*}

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ABSTRACT

Binary mass transfer via Roche-lobe overflow (RLOF) is a key channel for producing stripped-envelope Wolf-Rayet (WR) stars and may be critical to account for Type Ib/c supernova progenitors. RY Scuti is an extremely rare example of a massive binary star caught in this brief but important phase. Its unusual toroidal nebula indicates equatorial mass loss during RLOF, while the mass-gaining star is apparently embedded in an opaque accretion disk. RY Scuti’s toroidal nebula has two components: an inner ionised double-ring system, and an outer dust torus that is roughly twice the size of the ionised rings. We present two epochs of *L*-band Keck natural guide star adaptive optics (NGS-AO) images of the dust torus, plus three epochs of *Hubble Space Telescope* (*HST*) images of the ionised gas rings. Proper motions show that the inner ionised rings and the outer dust torus, while having similar geometry, came from two separate ejection events roughly 130 and 250 yr ago. This suggests that WR star formation via RLOF in massive contact binaries can be accompanied by eruptive and episodic bursts of mass loss, reminiscent of luminous blue variables (LBVs). We speculate that the repeating outbursts may arise in the mass gainer from instabilities associated with a high accretion rate. In the case of RY Scuti, we know of no historical evidence that either of its mass-loss events were observed as luminous outbursts, but if discrete mass-loss episodes in other RLOF binaries are accompanied by luminous outbursts, they might contribute to the population of extragalactic optical transients. When RLOF ends for RY Scuti, the overluminous mass gainer, currently surrounded by an accretion disk, will probably become a B[e] supergiant and may outshine the hotter stripped-envelope mass-donor star that should die as a Type Ib/c supernova.

Key words: binaries: eclipsing — binaries: general — circumstellar matter — stars: evolution — stars: mass loss — supernovae: general

1 INTRODUCTION

RY Scuti is a remarkable blue supergiant eclipsing binary system at a distance of 1.8 kpc (Smith et al. 2002). It has a well-determined period of only 11.1247 days (Smith et al.

2002), and the shape of the eclipse light curve suggests that it is in an advanced stage of Roche-lobe overflow (RLOF) (Antokhina & Cherepashchuk 1988; Guircin & Mardirossian 1981; Antokhina & Kumsiashvili 1999; Djurasevic et al. 2001; Melikian et al. 2010). RY Scuti belongs to the class of W Serpentis massive binaries, where significant mass transfer has led to an opaque disk around the mass-gaining star (Plavec 1980), and it has the shortest known period among examples of the class.

Most recent studies of the system’s radial velocity variations converge on a binary system with an $\sim 8 M_{\odot}$ primary and a $\sim 30 M_{\odot}$ secondary (Antokhina & Cherepashchuk

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1988; Skul'skii 1992; Sahade et al. 1992; Antokhina & Kumsiashvili 1999; Grundstrom et al. 2007). The $8 M_{\odot}$ primary is an O9/B0 supergiant, and is thought to have initially been the more massive of the two, but has transferred much of its mass to the secondary. (The likely initial masses of the primary and secondary were then of order 20-25 and 15-20 M_{\odot} , respectively.) It has been suggested that the mass-gaining secondary, probably an O5 star, is enshrouded by an opaque accretion disc (King & Jameson 1979; Antokhina & Cherepashchuk 1988; Antokhina & Kumsiashvili 1999). For recent discussions of the detailed properties of the circumstellar nebula and the binary system, we refer the reader to Smith et al. (2002) and Grundstrom et al. (2007), respectively. These authors review the literature concerning spatially resolved structure in the nebula (Hjellming et al. 1973; Gehrz et al. 1995, 2001; Smith et al. 1999, 2001, 2002), the unusual high-excitation spectrum with multiple-peak line profiles (Merrill 1928; Swings & Struve 1940; de Martino et al. 1992; Skul'skii & West 1993; Smith et al. 2002), and the photometric and spectroscopic variability of the eclipsing binary (Cowley & Hutchings 1976; King & Jameson 1979; Antokhina & Cherepashchuk 1988; Skul'skii 1992; Kumsiashvili et al. 2007; Djurasevic et al. 2001, 2008; Grundstrom et al. 2007).

Detailed study of RY Scuti and its nebula are of broader interest to the evolution of massive stars in two chief respects, as follows.

(1) Based on the He-rich abundances of its nebula, the masses of the stellar components, the orbital configuration, and the evolutionary state, it has been proposed that the O9/BO supergiant primary will soon evolve to a Wolf-Rayet (WR) star as a result of binary mass transfer, and that RY Scuti therefore represents an immediate precursor to a massive WR+OB binary system (Guircin & Mardirossian 1981; Antokhina & Cherepashchuk 1988; Smith et al. 2002). As such, it provides a rare glimpse at the formation of WR-like stars in binary systems, and hence, one of the two chief channels for producing progenitors of Type Ib/c supernovae (SNe). SNe Ibc are core-collapse SNe arising from massive “stripped-envelope” progenitors that have shed their outer H layers, and in some cases their He layers as well; see Filippenko (1997) for a review. The first evolutionary channel for making WR stars is where massive stars with initial masses above 30–35 M_{\odot} shed their H envelopes by virtue of their own mass loss in stellar winds or eruptions (Conti 1976; Smith & Owocki 2006). A second evolutionary channel, which is the only one available to less massive stars whose winds are too weak to reach the WR phase on their own, is to have their H envelope (and possibly also the He envelope) stripped via RLOF in a close binary system (e.g., Paczyński 1967; Podsiadlowski et al. 1992; Petrovic et al. 2005). Recent evidence from the observed statistics of SNe argues that RLOF may be the dominant channel for producing progenitors of SNe Ibc (Smith et al. 2011; see also Yoon et al. 2010; Dessart et al. 2011). The mass-transfer phase in massive binaries is thought to be brief, lasting only $\sim 10^4$ yr (Petrovic et al. 2005). RY Scuti is an extremely rare example of a massive binary star caught in this critical phase, and it may be the only known example with a bright spatially

resolved circumstellar nebula.¹ Its properties are therefore valuable for checking the conclusions drawn from studies of WR+OB systems already in the post-mass-transfer phase.

(2) RY Scuti may provide important clues to formation of toroidal and bipolar nebulae. Close binaries and mergers are often invoked to explain the formation of bipolar nebulae and rings like those around SN 1987A and other massive stars (Morris & Podsiadlowski 2006; Collins et al. 1999), although asymmetric mass loss from rapidly rotating stars has also been proposed for such nebulae and disks (Owocki 2003; Owocki et al. 1996; Dwarkadas & Owocki 2002; Smith 2007; Smith & Townsend 2007; Chiřă et al. 2008). One of the ambiguities for many nebulae is the lack of independent evidence that the central stars are (or were) binaries, and the role that binarity might have played in shaping the nebulae is therefore unknown. RY Scuti has the distinct advantage that it is an eclipsing system, so that its binary stellar parameters are known quite well. It is in a state of overcontact where RLOF is occurring and significant mass loss and mass transfer has taken place. Its nebula is toroidal, not bipolar, and so the observed morphology of RY Scuti's mass loss may provide important constraints on models for shaping nebulae with close binary influence.

The structure and dynamics of RY Scuti's nebula can aid our understanding of the role binarity plays in producing SNe Ibc progenitors and in determining nebular morphology. The structure, morphology, and kinematics of the nebula provide clues to its formation, while the age of its components give a record of the system's recent mass-loss history.

Previous observations by Gehrz et al. (1995, 2001) and Smith et al. (1999, 2001, 2002) have established that RY Scuti is 1.8 ± 0.1 kpc distant and that its toroidal nebula is separated into two components: an outer dust torus with a diameter of $\sim 2''$ or 3600 AU, and an inner ionised torus with a diameter of $\sim 1''$ (1800 AU). The mass of the dust torus is $\sim 10^{-6} M_{\odot}$ (dust only), and the ionised inner component has a gas mass of at least 0.003 M_{\odot} . The ionised component has an unusually high-excitation spectrum (Merrill 1928; Swings & Struve 1940; de Martino et al. 1992; Smith et al. 2002), and displays evidence for significant He and N enrichment (Smith et al. 2002). In high-resolution images taken with the *Hubble Space Telescope* (HST) by Smith et al. (1999, 2001), the inner ionised torus appears to break up into a pair of plane-parallel rings, analogous to the polar rings of SN 1987A, but confined much more closely to the equatorial plane (i.e., at latitudes of $\pm 14^\circ$ from the equator, rather than $\sim 45^\circ$ as in SN 1987A). The ionised rings are expanding with Doppler shifts of roughly $\pm 42 \text{ km s}^{-1}$, and an initial (although imprecise) measurement of their proper-motion expansion has been made in two epochs of HST images separated by ~ 2 yr, combined with two epochs of radio continuum images obtained with the Very Large Array that were separated by 9 yr. These data implied an ejection episode sometime in the late 19th century (Smith et al. 2001). The

¹ Another interesting example may be the radio-bright source W9 in the Galactic Centre region (Dougherty et al. 2010), but that source is much farther away, its nebula has not been spatially resolved, and it is not an eclipsing system.

Table 1. Imaging Observations of RY Scuti

Date	Tel./Instr.	Filter	Exp.
1997 Jun 01	<i>HST</i> /WFPC2	F656N	5s, 2×20 s, 2×120 s
2000 Feb 21	<i>HST</i> /WFPC2	F656N	2×10 s, 2×120 s
2009 Apr 19	<i>HST</i> /WFPC2	F656N	2×10 s, 2×260 s
2009 Apr 19	<i>HST</i> /WFPC2	F658N	2×18 s, 2×350 s
2003 Jun 11	Keck/NIRC2 AO	L_p	5×10.6 s, 53 s total
2009 Aug 27	Keck/NIRC2 AO	L_p	10×5.3 s, 53 s total

kinematics of the outer dust torus were unknown before the present study.

In this paper, we present a third epoch of *HST* images, extending the time baseline for proper motions made with the same instrument to more than a decade. We also present the first adaptive-optics (AO) images of RY Scuti obtained in the thermal infrared (IR), providing the sharpest picture yet of the structure in the outer dust torus. We obtained two epochs of AO images in the same filter with the same instrument, separated in time by 6 years, and we use these to measure for the first time the expansion rate of the dust torus separately from the ionised gas. We describe the observations in §2, the multi-wavelength morphology in §3, and the results from proper-motion measurements in §4. In §5 we discuss implications for the formation of non-spherical nebulae and for SN Ib/c progenitors, and speculate about optical transients associated with episodic RLOF events in massive binaries. We summarise our conclusions in §6.

2 OBSERVATIONS

We obtained multi-epoch high-resolution observations of RY Scuti, using *HST* images to trace the inner ionised rings and Keck Observatory L -band images to trace the outer dust torus in the IR. The log of observations is listed in Table 1.

2.1 Multi-Epoch HST Imaging

Three epochs of images of RY Scuti were obtained with the *HST* Wide Field Planetary Camera 2 (WFPC2) using the F656N ($H\alpha$) filter, plus single epochs with the F658N ([N II] $\lambda 6583$; see below) and F953N ([S III] $\lambda 9532$) filters. The first two epochs of $H\alpha$ images were published and analyzed previously (Smith et al. 1999, 2001). For the third epoch of $H\alpha$ observations, we implemented the same observing strategy and followed the same data-reduction steps as for the first two. This involved combining a series of exposures with a range of exposure times to correct for CCD blooming from the bright central star, as well as a careful subtraction of a model point-spread function (PSF) generated by the Tiny-Tim software, as described in the earlier papers. The PSF subtraction is necessary because the extended diffraction pattern in the PSF from the bright central star can interfere with and mask the nebular structures. After PSF subtraction, the newest epoch of images confirms the same structures seen in our earlier studies, but taken with a different roll angle and orientation of the PSF diffraction spikes.

Our goals in obtaining a third epoch were to confirm our previous detection of expansion of the rings made with a short temporal baseline (Smith et al. 2001) and to thereby

improve the precision of the ejection age for comparison with that of the outer torus. For the proper-motion measurements, we use the F656N ($H\alpha$) filter as it is the only one available in all three epochs. The F658N image is useful to investigate any possible spatial gradients in ionization structure in the rings. The elapsed time between the second epoch and the first is 994.43 days, or $\Delta t = 2.723$ yr. The last epoch extends this temporal baseline to 4340.13 days, or $\Delta t = 11.883$ yr since epoch 1.

2.2 Keck NIRC2-AO Imaging

Using the Keck II AO system (Wizinowich 1999) with the instrument NIRC2, we obtained two epochs of L -prime (hereafter L_p) images. They were acquired with the narrow camera (10 mas pixel⁻¹ scale) making use of a five-point box dither pattern with a 1''.0 step size. Due to the peak brightness of the RY Scuti central point source, a square subarray of 512 pixels (out of 1024) was employed so that the minimum exposure time could be set to 50 ms, thus avoiding saturation. The dominant source of background at 3.8 μ m is the thermal radiation of the AO system telescope optics. Dust on the 11 ambient-temperature optical surfaces that are in the path of NIRC2 are a significant source of background. Frequent dithers were used to reduce time varying effects of the background. RY Scuti ($V = 9.14$ mag) provides plenty of visible-light flux to the AO wavefront sensor, allowing the frame rate to be set to a relatively high frequency; it was 700 Hz in 2003 and 1500 Hz in 2009. Higher frequencies became possible thanks to an upgrade of the wavefront controller (van Dam 2007). The AO performance was superb, in both cases resulting in diffraction-limited resolution of about 72 mas with a Strehl greater than 70%. The PSF is well sampled in the NIRC2 narrow-camera plate scale.

The data reduction was performed in the customary method for IR imaging data. Before shifting and coadding the 3-point dithered data, we flat-fielded the images using normalised flats constructed from sky-only data acquired 1' north of the nebula. The flattened images were then background subtracted using the sky images. The images were aligned using the centroid of RY Scuti's central point source. The initial goal was to produce the best image yet of the IR dust torus with diffraction-limited imaging in the near-IR to complement the previous Keck mid-IR images obtained with the long-wavelength spectrometer (Gehrz et al. 2001). The subsequent goal of the later-epoch observation was to measure the expansion of the outer dust torus separately from the inner ionised gas nebula.

3 MULTI-WAVELENGTH STRUCTURE

We investigated the multi-wavelength structure of the nebula by comparing the IR and optical images. The morphology of the optical images in $H\alpha$ was already discussed in detail in previous papers (Smith et al. 2002, 2001, 1999). The NIRC2-AO images in the L band provide the highest-resolution images of the dust torus so far. They are comparable in spatial resolution to the *HST* images, permitting the first meaningful comparison between the two. Figure 1 shows a colour composite comparing the *HST* image to the

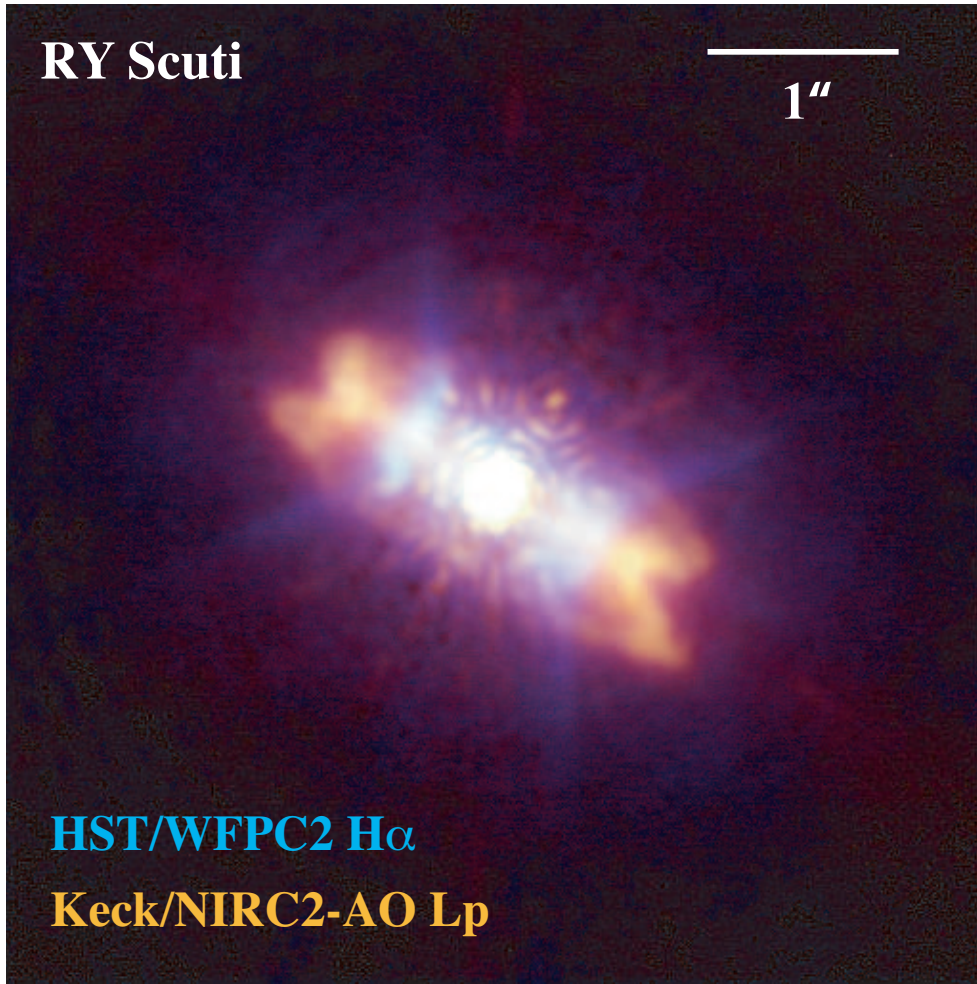


Figure 1. A colour composite of the ionised gas traced by the *HST*/WFPC2 image taken through the F656N $H\alpha$ filter (blue-green) and the warm dust traced by the Keck/NIRC2-AO image in the L_p filter (red-orange).

near-IR Keck-AO L_p image, while Figure 2 provides various comparisons of multi-wavelength data from the present study and from a previous study of thermal-IR Keck images by Gehrz et al. (2001).

The first-epoch 2003 image of RY Scuti obtained with NIRC2-AO is shown in Figure 2a. The combination of AO and the better diffraction limit at $\sim 4 \mu\text{m}$ as compared to $\sim 10 \mu\text{m}$ means that this L_p -band image provides the sharpest view yet of the structure in the dust torus around RY Scuti, improving the spatial resolution from our previous thermal-IR Keck images without AO (Gehrz et al. 2001) by a factor of 2–3. The warm-dust emission in this filter traces the same dust responsible for the torus observed at longer wavelengths. This is evident from Figure 2b, which shows the same NIRC2-AO image from Figure 2a with the contours of $11.7 \mu\text{m}$ emission from Gehrz et al. (2001) superposed. Allowing for differences in spatial resolution (and for stronger photospheric emission from the central star at shorter wavelengths), the L_p -band image has the same spatial distribution as the $11.7 \mu\text{m}$ thermal-IR emission. This was expected, since the 2–20 μm spectral energy distribution (SED) of the dust torus can be fitted with a single dust temperature (Gehrz et al. 2001). In other words, the L_p fil-

ter at $3.8 \mu\text{m}$ samples the Wien tail of the same 300–400 K dust whose emission peaks at $\sim 10 \mu\text{m}$, rather than sampling hotter dust closer to the star. The new AO image indicates a very thin distribution of dust in the radial direction, consistent with our findings below that the dust torus originated in an episodic ejection from the star.

The NIRC2-AO images show unprecedented detail of the structure in the IR torus. The toroidal nebula obviously appears pinched at the waist, flaring above and below the equator. This appearance could be due to the overlap of two inclined rings, as in the optical images, or it could be that the dust torus is akin to an hourglass structure with the top and bottom chopped off. In either case, the dust torus appears to have a sharp outer boundary, and we see no evidence in either the *HST* or near-IR images for faint extensions of a larger hourglass structure. Overall, the structure of the IR dust torus resembles the morphology seen in the inner ionised rings, but with roughly twice the size.

The near-IR AO images reveal no clear evidence for an enhancement of dust emission from parts of the nebula inside the dust torus, consistent with the single-temperature dust SED as noted above. In particular, there is no enhancement of IR emission coincident with the ionised structures of the

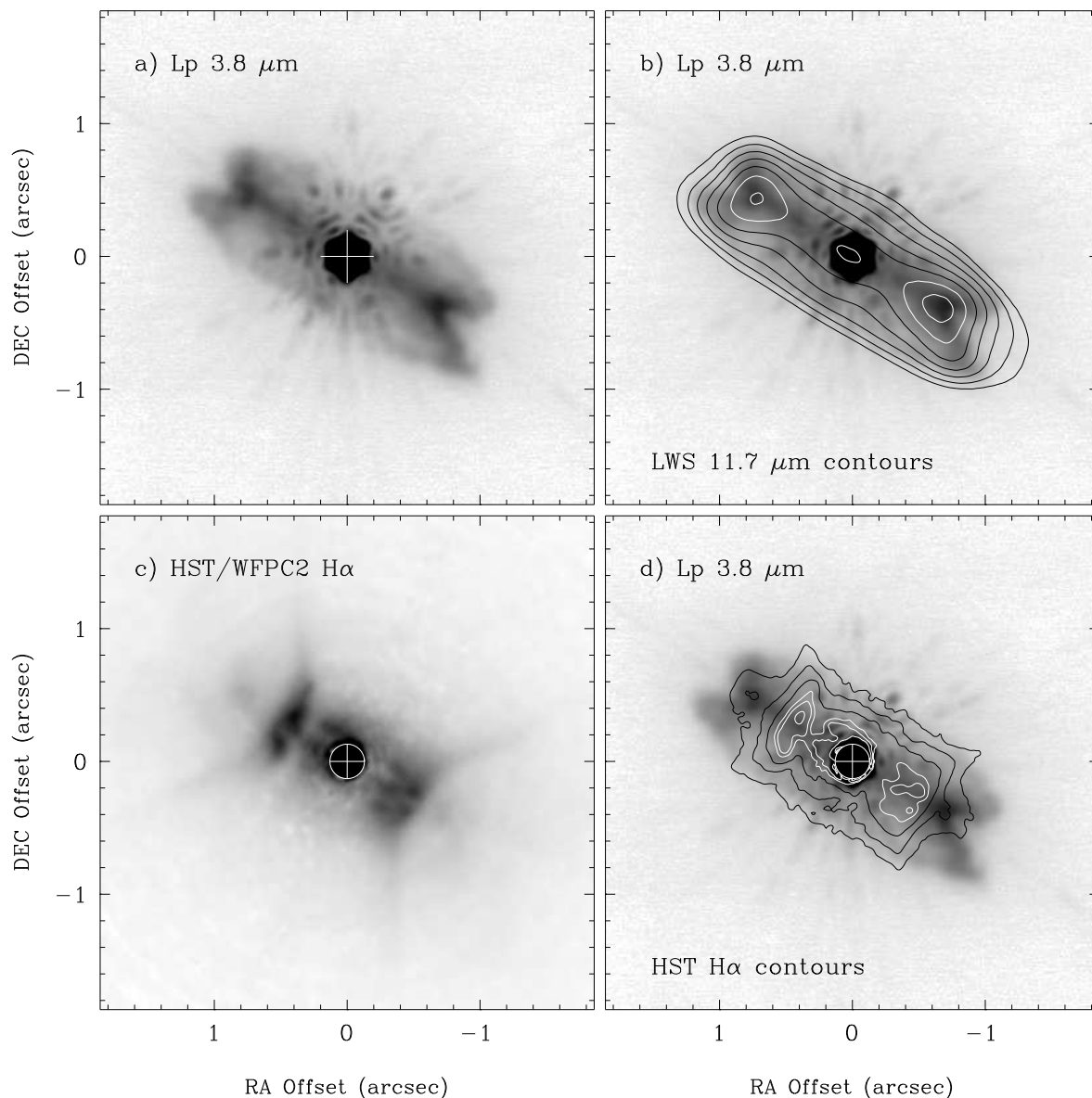


Figure 2. (a) The first-epoch 2003 June 11 L_p -band NIRC2-AO image of RY Scuti (the second epoch looks identical, except for a different orientation of the diffraction pattern). (b) Same image as in (a), but overlaid with contours of the $11.7\ \mu\text{m}$ image from Gehrz et al. (2001). (c) The PSF-subtracted *HST*/WFPC2 $\text{H}\alpha$ (F656N) image of RY Scuti. (d) The L_p -band image from (a) overlaid with contours of the *HST* image.

inner rings seen in $\text{H}\alpha$ images with *HST* (except for some spurious features associated with the Keck PSF). Since the inner rings are closer to the star and any dust therein would be hotter and more easily detected at short IR wavelengths, we conclude that the inner rings have a much lower dust mass than the outer rings. The second mass-ejection event that produced the inner rings evidently did not form dust as efficiently – at least not yet. Given that the temperature of the outer dust torus is 300–400 K (Gehrz et al. 2001), the equilibrium grain temperature in the inner rings (at roughly half the distance from the same star) should be about 420–560 K. Since the condensation temperature of dust grains is typically $\gtrsim 1000$ K, any dust that was destined to form in the inner rings should have done so already. An inter-

esting possibility is that the second ejection, which formed the inner ionised nebula, was able to shield the outer torus from ionising radiation, thereby allowing it to form dust. One could speculate, then, that a hypothetical future ejection might be needed to shield the inner torus seen now in *HST* images in order to facilitate dust formation in that feature.

The higher resolution of the new near-IR AO images reveals for the first time a clear gap between the inner ionised rings and the outer dust torus. Figure 3 shows tracings across the middle of the Keck IR and *HST* images (see below), both as observed in 2009. For comparison, Figure 3 also shows very simple, idealised models for the optically thin intensity from a cross section through the middle of the

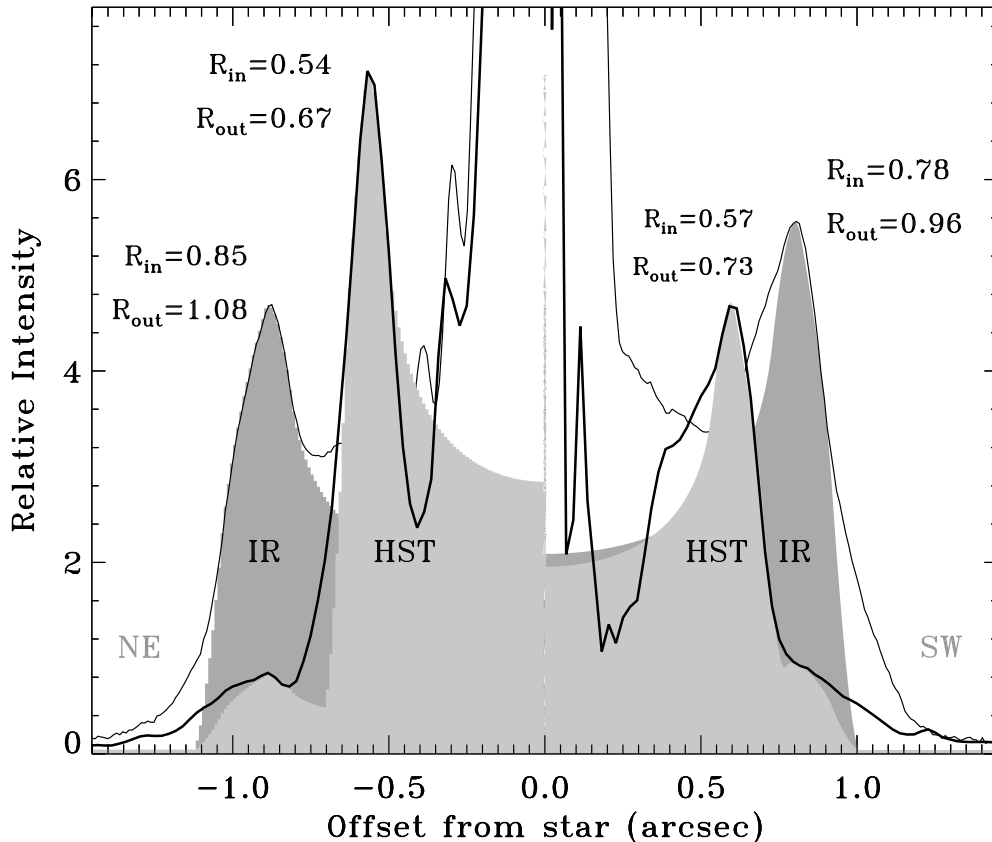


Figure 3. Spatial intensity scans across the major axis in the 2009 PSF-subtracted *HST* H α image (thick line) and the 2009 Keck IR image (thin line), along a position angle of 60°. For comparison, the shaded regions show simple models for the intensity of a slice through an idealised optically thin edge-on torus, with inner and outer radii noted above each peak. We used different parameters for the NE and SW sides due to the inherent asymmetry of the nebula. The darker and lighter shaded regions respectively approximate the intensity cut across the IR torus and the inner ionised rings seen by *HST*. This lighter shaded region includes a broader base that is an arbitrarily scaled version of the IR torus (to mimic the scattered H α light from the outer nebula; see Smith et al. 2002).

geometrically thin shell (see Smith et al. 2007 for more details). These simple models are not perfect matches to the data due to the non-azimuthally symmetric density structure of the ionised rings (Smith et al. 2002). While the NE side of the nebula matches the simple models rather well, the SW portion deviates — and interestingly, both the inner ionised rings and the outer dust torus deviate from the model on the SW side in the same manner. This requires that both the inner and outer tori *deviate from azimuthal symmetry in a similar way*. This is probably an important clue to the ejection mechanism that formed them.

The simple models in Figure 3 allow us to provide rough estimates of the inner and outer radii for both the ionised and dusty tori. These values are listed in Figure 3, and we note that the values derived from images of the inner ionised component agree with the thickness inferred from STIS spectroscopy (Smith et al. 2002). The radial thicknesses of the model shells are 23–28% of their radii. More importantly, there is a clear gap between the inner edge of the IR torus and the outer edge of the ionised rings (i.e., the structures do not touch or overlap). This is most evident on the NE side of the nebula (Figure 3), and is clear in the colour image in Figure 1 as well, indicating a spatial separation of the dust and ionised gas. Physically, this is quite meaningful; it

indicates that the outer boundary of the ionised rings is not caused by a simple ionization front, because in that case we would expect non-ionising UV photons to penetrate the ionization front and heat the dust immediately outside it. The large separation instead suggests that the IR peak is a separate density enhancement at a larger radius where the remaining UV radiation is absorbed. (The inner ring may nevertheless play an important role in shielding the outer dust torus, but our point here is that the outer boundary of the ionised torus is caused by a drop in density, not an ionization front.) As we show below, proper motions indicate that the outer IR dust torus is older and originated in a separate mass-ejection event. The spatial gap between the inner and outer rings indicates that the outer ring was not responsible for shaping the inner ring, because they are not interacting hydrodynamically.

In the ionised inner torus, the NE peak is much brighter than the SW peak. For the IR torus, the reverse is true. Perhaps this is because the NE side of the IR torus is shielded by a denser inner nebula, as compared to the SW side. Of course, these differences may be due purely to different density distributions as well.

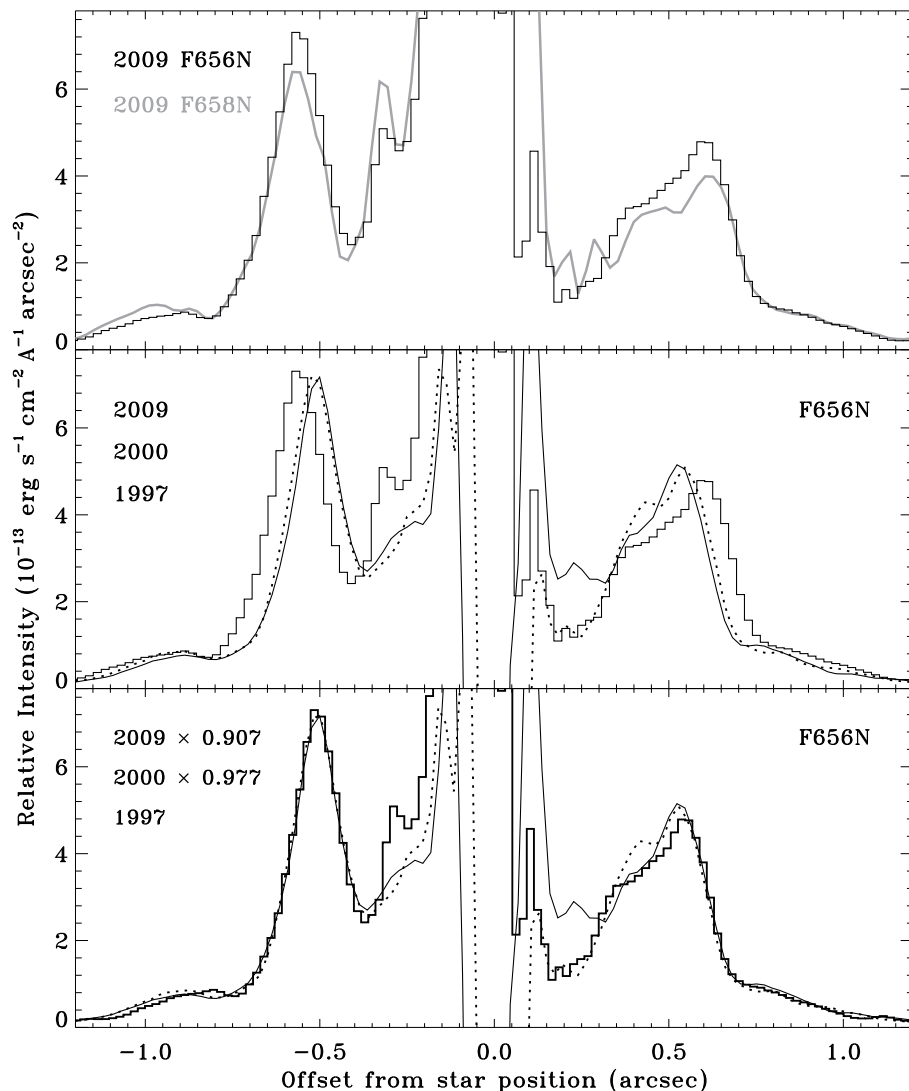


Figure 4. Spatial intensity scans across the major axis in PSF-subtracted *HST* images. The top panel shows tracings for $H\alpha$ F656N (solid black) and $[N II]$ F658N (solid grey) in the newest epoch from 2009. The middle panel gives the tracings through $H\alpha$ images at all three epochs in 1997 (solid), 2000 (dotted), and 2009 (solid histogram). The bottom panel is the same as the middle, except that the sizes of the 2000 and 2009 intensity scans have been multiplied by 97.7% and 90.7% of their observed size, respectively, to match the size in the 1997 image.

4 PROPER MOTIONS OF THE TWO COMPONENTS

4.1 The Inner Ionised Rings with HST

By aligning the three epochs of *HST* images, we were able to confirm that the expansion of the rings is primarily homologous (i.e., self-similar radial expansion). When an image taken at an early epoch is magnified by some scaling factor, it looks identical to one taken at a later epoch. We detect no evidence for non-radial motion, acceleration, or deceleration in the expanding nebula.

To quantify the fractional increase in size between epochs, we scaled later images so that the nebular structure matched that in the first epoch, and then performed a cross correlation of the scaled image to estimate the best

scaling factor. This is similar to the method employed by Morse et al. (2001) for measuring proper motions in *HST* images of η Carinae, except that here we adopted a multiplicative size-scaling factor for the whole nebula (with central regions near the star masked out) rather than measuring translational shifts independently for many individual small condensations. The former method is well suited to the compact size and simpler structure of RY Scuti's nebula.

To illustrate the scaling between epochs, Figure 4 (middle panel) shows intensity tracings across the major axis of the nebula through the emission peaks on either side of the star at each epoch. One can see that the nebula is clearly expanding with time. The bottom panel in Figure 4 shows the same tracings, but with the pixel size scale of the 2009 and 2001 images reduced to match the structure in the 1997

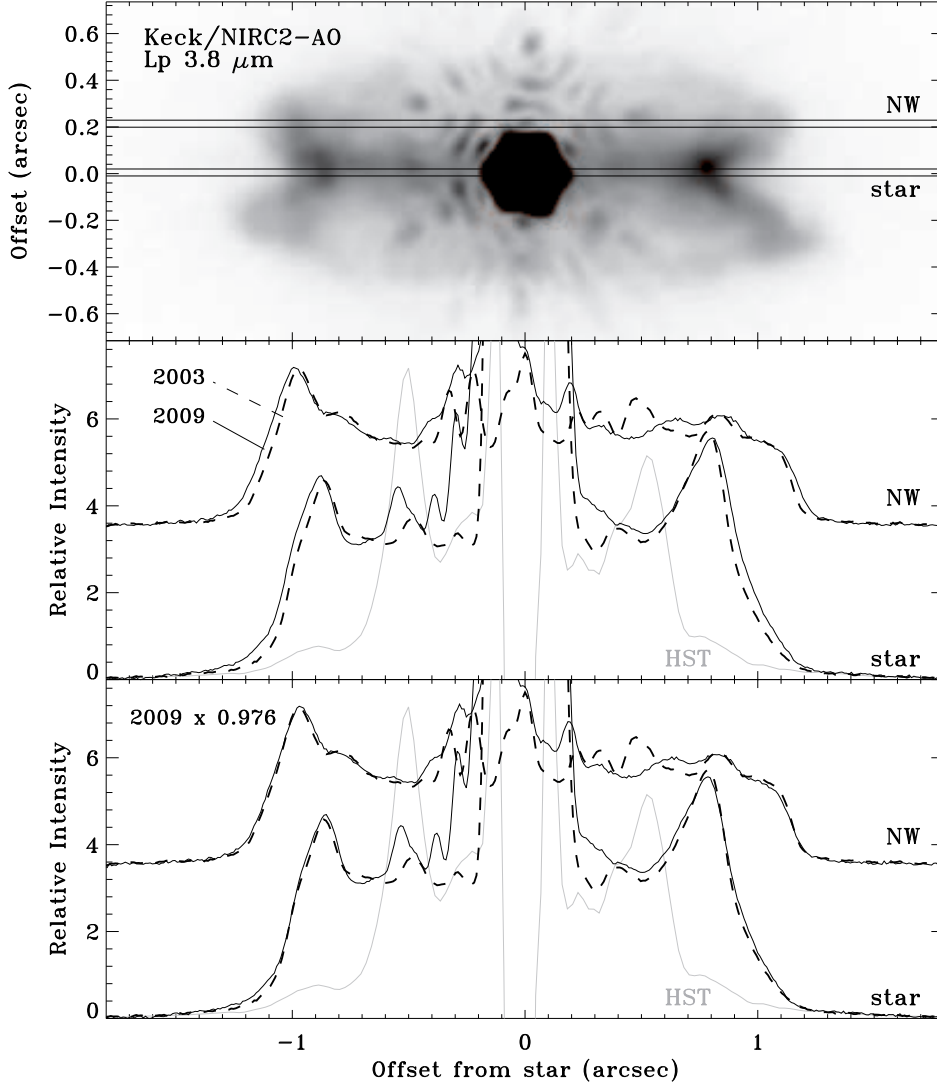


Figure 5. Proper motions of the IR torus in Keck/NIRC2-AO images. The top panel shows the 2003 June 11 image of RY Scuti in the L_p band obtained with Keck/NIRC2-AO, rotated counterclockwise by 30° (note that many features within $0''.5$ of the star are part of the PSF diffraction pattern of the Keck telescope). The horizontal lines marked “star” and “NW” give the positions of intensity tracings across the image, shown in the middle and bottom panels. The middle panel displays the intensity scans for these two positions (with a constant offset added to the “NW” tracing) as observed in 2003 June (dashed) and 2009 August (solid). The bottom panel is the same as the middle, except that the size of the 2009 intensity scan has been multiplied by 97.6%, giving the best match to the 2003 image (both “star” and “NW” tracings were scaled by the same factor). The light-grey curve shows the same tracing of $H\alpha$ from the *HST* data in Figure 4.

image. Similar tracings for the Keck images are shown in Figure 5.

We define the scale factor ϵ by which the size of the nebula at epoch 2 (R_2) must be reduced to match the radius at epoch 1 (R_1) as $\epsilon = R_1/R_2$. In terms of this scaling factor ϵ , the age of the nebula t (the time since ejection relative to epoch 2) is given by

$$t = \Delta t \times (1 - \epsilon)^{-1}, \quad (1)$$

where Δt is the time period that has elapsed between the images at epochs 1 and 2. We define epochs 1, 2, and 3 as the images taken in 1997, 2000, and 2009, respectively. From the dates of observations, $\Delta t_{1,2} = 2.7226$ yr and $\Delta t_{1,3} = 11.8826$

yr. By cross correlating the NE and SW peak structures at different epochs, we measure $\epsilon_{1,2} = 0.977 \pm 0.003$ and $\epsilon_{1,3} = 0.907 \pm 0.003$. Equation (1) then yields ages of $t_{1,2} = 118.4 \pm 16$ yr (relative to 2000) and $t_{1,3} = 127.8 \pm 4.2$ yr (relative to 2009). The uncertainties are Gaussian 3σ error bars resulting from the spatial cross-correlation of each pair of epochs. Thus, the baselines between epochs 1 and 2 (1997–2000) and between epochs 1 and 3 (1997–2009) both agree on an ejection date around the year 1881 for the ionised torus. We adopt an uncertainty of ± 4.2 yr in the age and ejection date, since it corresponds to the longer temporal baseline with a more precise measurement. Note that this measurement is independent of the precision to which we

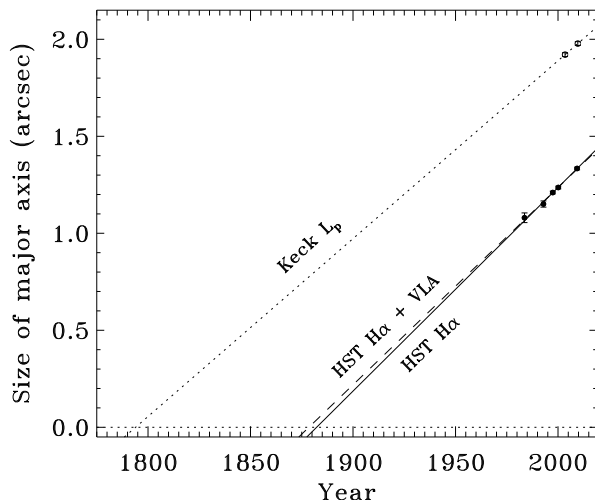


Figure 6. Plot of the increase in the width of the major axis of RY Scuti’s nebula with time; the width is measured consistently at half the peak intensity level. Unfilled points correspond to the IR torus measured in Keck L_p images obtained in 2003 and 2009, while the filled points correspond to the ionised rings measured in archival VLA data from 1983 and 1992 (from Smith et al. 2001) and $HST/H\alpha$ images obtained in 1997, 2000, and 2009. The dotted line extrapolates the expansion rate measured from the two Keck points. The dashed and solid lines show least-squares fits for the expansion of the ionised rings with the first two VLA data points included and excluded, respectively, along with the subsequent three HST images.

can spatially align the central star in the images, since we are simply measuring the growth in size across the nebula, not the distance from the star.

Figure 6 shows the expansion of RY Scuti’s nebula in a different way. This is an updated version of Figure 3 from Smith et al. (2001), including the new Keck data and the last epoch of HST imaging. It shows measurements of the width of the major axis of the nebula measured at half the peak intensity. For the ionised rings, this includes the images of radio free-free emission obtained with the VLA in 1983 and 1992, as well as the three epochs of $H\alpha$ imaging in 1997, 2000, and 2009. The dashed and solid lines show a linear least-squares fit (weight $\propto \sigma^{-1/2}$) to the expansion rate of the ring with (dashed) and without (solid) the early VLA data included in the fit. These fits yield ejection dates of 1878 ± 5 and 1883 ± 6 , respectively, for the ionised component of the nebula, consistent with the ejection date of 1881 ± 4 derived from the first method discussed above. The dotted line extrapolates the expansion rate measured the same way in the IR Keck images; this is not a fit since there are only two points. The implied ejection date of 1794 ± 30 yr for the dust torus is younger than that derived below, but is consistent within the uncertainty.

4.2 The Outer Dust Torus with Keck AO

We employed the same method of measuring the expansion of the dust torus in IR images as described above for the HST images, except that for the IR images we had only two epochs. Figure 5 shows intensity tracings across the long axis of the dust torus at two positions, indicated in the top panel.

The middle panel displays the tracings for the two epochs at the two sampled positions, while the bottom panel illustrates the same tracings except that the 2009 epoch has been scaled to match the 2003 image (see discussion above concerning the HST images and Fig. 4). The two different position samples are consistent with the same expansion rate.

The comparison of the 2003 and 2009 Keck images of the IR dust torus shows that the size of the torus in 2003 was $97.6\% (\pm 0.3\%)$ of the size observed in 2009 (i.e., $\epsilon_{1,2} = 0.976 \pm 0.003$). Since the time elapsed between images was $\Delta t = 6.216$ yr, Equation (1) indicates that the dynamical age of the dust torus is 255 ± 32 yr, implying an ejection date around the year 1754. This is more than twice the age of the inner ionised rings determined above from HST images, so the two components cannot be the result of the same mass ejection. The age derived from this method is consistent within the uncertainty with the age derived from the simpler method described above and shown in Figure 6, where we measured the changing width of the major axis of the nebula at half the peak intensity, following Smith et al. (2001). This simpler method is more susceptible to error caused by changes in spatial resolution, which is more of a concern in ground-based data than in HST data having a more consistent PSF. We therefore favour the ejection date around 1754.

5 DISCUSSION

5.1 Formation of the Double Rings

The mechanism for the formation of the rings around SN 1987A has presented an enduring mystery that has no obvious answer (e.g., Blondin & Lundqvist 1993; Burrows et al. 1995; Martin & Arnett 1995; Collins et al. 1999; Morris & Podsiadlowski 2005), but one expects that the formation mechanism of the rings might also be an important clue to understanding the peculiar nature of the blue progenitor star Sk −69 202. Smith et al. (2007) noted a population of stars with equatorial rings that are analogous to the equatorial ring around SN 1987A, including RY Scuti. Only one other object, the luminous blue variable (LBV) star HD 168625, is known to have triple rings similar to those of SN 1987A (Smith 2007). RY Scuti has a set of double ionised rings which are not identical to those of SN 1987A, but may be related.

One can test some models for formation of double rings by measuring the expansion dynamics of the rings – i.e., do they exhibit homologous expansion, non-radial expansions, or other peculiar motions or time-variable illumination? Models with aspherical ejection from the star system would predict homologous expansion at these large distances. On the other hand, models such as those of Chiřă et al. (2008) have the rings produced by a bipolar wind pushing through a previously ejected thin shell, with the two structures colliding and forming rings at their intersection. In this model, the apparent ring structure originates where the rings are observed, rather than the shaping mechanism arising close to the star. It would predict motion of the rings toward the equatorial plane with time as the inner bipolar wind sweeps through the thin spherical shell, with the intersection migrating from the pole to the equator (see Chiřă

et al. 2008). We therefore conclude that models such as the one discussed by Chiřa et al. (2008) do not apply in the case of RY Scuti, since the nebula is expanding homologously.

A broad class of hydrodynamic models involves the formation of bipolar nebulae by the interaction of a wind with a previously ejected equatorial density enhancement; essentially, a pre-existing disk or torus pinches the waist of subsequently ejected material to produce an hourglass shape. A model by Morris & Podsiadlowski (2007) accounts for the formation of SN 1987A's nebula with a merger of a binary system, where the merger ejects an equatorial torus or disk of material that might then divert a faster wind toward high latitudes, forming a pair of polar caps that could be seen as rings under proper circumstances of illumination. That merger model cannot apply here, since RY Scuti has not yet merged. More importantly, the gap between the two components indicates that the second mass ejection is not yet interacting hydrodynamically with the first one, even at this very young stage, so the formation of its rings must have a different origin that doesn't depend on hydrodynamic shaping by a previously ejected disk.

Instead, the proper motions in RY Scuti's nebula suggest that on at least two separate occasions separated by only ~ 100 – 200 yr, the star system suffered some sort of outburst that ejected mass near the equator at relatively slow speeds (i.e., much slower than the escape speed or normal wind speed of either star). It also suggests that whatever mechanism shaped the first ejection was able to persist and have the same influence on the second, because both ejections have the same basic geometry and structure. The cause of such an outburst is unknown, but some ideas are discussed in §5.3. Here we focus on the shape of the ejecta, and we discuss two potential scenarios, the second of which we deem to be more likely.

(1) During an episode of increased mass loss or mass transfer from the primary star, RY Scuti may have suffered an enhancement of mass loss through the outer L2 Lagrangian point (see Figure 7). From the phase variability of absorption features such as He I lines, Grundstrom et al. (2007) inferred that RY Scuti does in fact have a mass-loss stream exiting the system through the L2 point in its present-day state. An increase in this mass-loss rate at two separate times in the past could lead to the creation of discrete toroidal structures that would expand outward to form the currently observed circumstellar nebula. One potential inconsistency is that the observed outflow through L2 has an expansion speed of ~ 200 km s $^{-1}$ (Grundstrom et al. 2007), whereas the toroidal circumstellar nebula has a much slower radial expansion of only ~ 40 km s $^{-1}$ (Smith et al. 2002).

Another problem with this scenario is that even with an enhancement of mass transfer and mass loss through L2, one would normally expect mass loss through the outer Lagrangian point to be a relatively slow process compared to the orbital period of only ~ 11 days, leading to azimuthally symmetric mass loss. Thus, while this scenario accounts for equatorially enhanced mass loss, it provides no compelling explanation for the nature of sudden outbursts or for the azimuthal asymmetry observed in RY Scuti's ionised rings. Furthermore, the origin of the double ionised ring structure is unclear in this scenario, unless the apparent separation between the rings is due to a shadow cast by an opaque cir-

cumbinary disk at inner radii much smaller than the size of the rings, as suggested by Grundstrom et al. (2007).

(2) A different scenario may be that the accreting secondary star experiences an outburst, and that the outflowing ejecta are immediately shaped by the accretion torus within a few stellar radii around the secondary (Figure 7). As we explain further in §5.3, invoking an outburst from the secondary is motivated by our speculation that the secondary may encounter a cyclical instability associated with the high mass accretion and angular momentum accretion rates currently imposed on it during RLOF.

Suppose that the envelope of the accreting secondary star becomes unstable and suffers a sudden outburst of mass loss. The ejecta that follow mid- to high-latitude trajectories toward the pole will expand unimpeded (represented by the dashed arrows in Figure 7), probably at very high speeds of ~ 1000 km s $^{-1}$, close to the escape speed of a main-sequence O-type star (recall that the secondary star in the RY Scuti system is thought to be a main-sequence O-type star that is hidden by its cooler, opaque accretion torus; Grundstrom et al. 2007). On the other hand, the ejecta expanding at low latitudes near the equator must contend with the presence of the massive, dense accretion torus. The stellar ejecta will be decelerated by this interaction, and perhaps some of the material on the surface of the accretion torus will be entrained by the outflow that is diverted above and below the torus. This will result in a much slower outflow from the system at latitudes immediately above and below the edges of the accretion torus (this is depicted by the solid short arrows in Figure 7). If the ejection is a sudden event, it will produce an enhancement of mass at specific latitudes above and below the equatorial plane, at a specific distance from the star (i.e., plane-parallel rings rather than a shell or conical structures).² In this scenario, it is the thickness of the accretion torus that sets the latitude and separation of the rings that we observe in the circumstellar nebula. The presence of a thick accretion torus reaching at least $\pm 15^\circ$ is required by the fact that the accretion torus obscures the secondary in a system with an orbital inclination of $i \approx 75^\circ$ (Smith et al. 2002). This roughly matches the latitudes of the nebular rings at $\pm 14^\circ$.

If a sudden (i.e., dynamical) outburst of the secondary star occurs on a time scale short compared to the orbital period, then it may provide a compelling explanation for the azimuthal asymmetry in the system as well: the parts of the outflowing ejecta that expand toward the bloated supergiant primary star must interact with that star and its wind. This would lead to a gap in the ejecta over a range of azimuthal angles covering 15–30% of the orbit. This is commensurate with the size of the gap on the near side of the nebula (Smith et al. 2002). Without a sudden outburst, one would expect the outflow to be azimuthally symmetric, contradicting observations.

Because a sudden ejection by the secondary star can, in principle, account for both the latitudinal and azimuthal distribution of mass in the nebula around RY Scuti, we find this scenario to be more compelling than option (1) discussed

² Note that if the mass ejection is related to critical rotation, as we speculate in §5.3, then it is possible that the mass ejection itself will be inherently non-spherical.

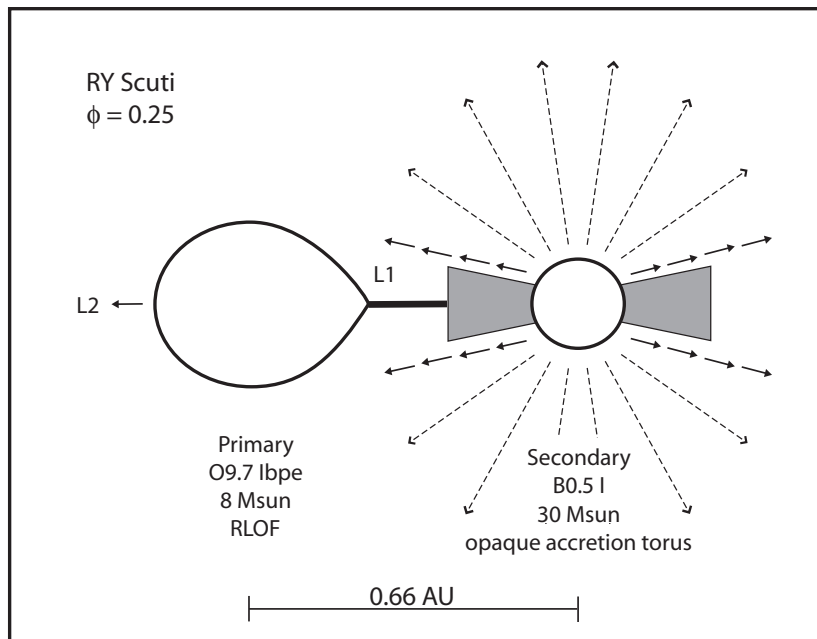


Figure 7. Sketch of the RY Scuti system as viewed from the equatorial plane near phase $\phi = 0.25$, adapted from the pole-on view of Grundstrom et al. (2007). The primary is filling its Roche lobe and transferring matter to the secondary, which is surrounded by an opaque accretion disk/torus. The long dashed arrows represent the trajectory of unimpeded wind or eruptive ejecta from the secondary. The shorter solid black arrows represent the trajectory of denser and slower disk material entrained by the secondary wind, or wind/ejecta that are decelerated through interaction with the torus. In a scenario where the accreting secondary suffers an outburst, this slower and denser material skimming the edge of the torus may form the rings around RY Scuti. With $M_1 + M_2 = 38M_\odot$ (Grundstrom et al. 2007) and $P = 11.12475$ d (Smith et al. 2002), the orbital semimajor axis is $a = 0.33$ AU.

above. Of course, our suggestion should be explored using detailed numerical hydrodynamic simulations. Some modelers have explored a wind interacting with a pre-existing disk or torus (e.g., Frank et al. 1995; Martin & Arnett 1995; Blondin & Lundqvist 1993). However, these simulations generally placed the constricting torus at a large distance from the ejection, rather than an accretion torus within a few stellar radii, and they adopted a continuous wind that rams into the torus rather than a sudden ejection (these simulations – usually in two dimensions – also do not account for the obstruction of a supergiant companion star, of course). The sudden ejection is key for both the ring structure and the azimuthal asymmetry. The potential for a sudden ejection by the secondary to account for the structure in RY Scuti’s circumstellar nebula motivates our speculation in §5.3 regarding possible physical causes of an outburst from the accreting secondary.³

5.2 Significance in Pre-Supernova Evolution, and Post-RLOF Binaries as B[e] Supergiants

Despite the recent episodes of mass ejection, estimates of the nebular mass compared to the amount of mass exchanged

between the stars suggests that RLOF has been mostly conservative so far for RY Scuti. The mass of the inner ionised gas torus is roughly $0.003 M_\odot$ (Smith et al. 2002), while the mass of the outer dusty torus (from the measured dust mass multiplied by an assumed gas:dust mass ratio of 100 adopted by those authors) is at least $1.4 \times 10^{-4} M_\odot$ (Gehrz et al. 2001). Thus, the total mass detected in the two-component toroidal nebula around RY Scuti is only of order $0.003 M_\odot$. This is admittedly a lower limit to the total mass lost, since there may be dense clumps of neutral gas not measured in the tracers of ionised gas. There could also be more mass in the equatorial plane at larger distances that is shielded from the star’s radiation by the inner components of the nebula, but this mass has not been constrained by any previous study. In any case, the nebular mass ejected in the past $\sim 10^4$ yr is probably far less than $1 M_\odot$. With a current stellar-wind mass-loss rate of around $(1-2) \times 10^{-6} M_\odot \text{ yr}^{-1}$ (typical for the wind of an O9 supergiant; Repolust et al. 2004), the mass lost in a fast line-driven stellar wind during this time should be comparable to that in the ionised nebula.

As noted in the introduction, however, modern observed parameters for RY Scuti favour present-day masses of $\sim 30 M_\odot$ for the secondary, and $\sim 8 M_\odot$ for the primary (originally the more massive star). Since the likely initial masses were of order 25 and $15 M_\odot$, this suggests that about $15 M_\odot$ has been shifted from the primary to the secondary during the brief ($\sim 10^4$ yr) RLOF phase, whereas much less than $1 M_\odot$ appears to have been lost from the system during that same time. From these rough observational estimates,

³ Note that the apparent thicknesses of the rings and dust torus, which are 20–25% of their respective radii, may simply be due to the sound speed multiplied by their ages. The radial expansion speeds are $40\text{--}50 \text{ km s}^{-1}$, which is 4–5 times the sound speed when the ejected gas is ionised. In other words, they are as thin as they can be, even for an instantaneous ejection.

we conjecture that the mass transfer in RY Scuti has been largely conservative — that is, unless a large amount of nebular material resides in the equatorial plane outside the dust torus where it may be shielded, and may therefore remain cold and largely neutral. Observations at far-IR and submm wavelengths may help constrain the amount of additional cold material in the system.

While conservative mass transfer rather than mass loss appears to dominate the stripping of the donor star’s H envelope, the mass ejected into an equatorial torus may play an important role in angular momentum loss. The resulting dusty toroid or ring may have observable consequences after the short phase of RLOF is complete, as noted earlier.

In the RY Scuti system, the primary has transferred much of its mass to the secondary, which as a result, is seen as a disk-enshrouded O-type supergiant star that will now be overluminous for its initial mass, and will be rapidly rotating due to the additional angular momentum of the accreted mass (see below). Eventually, when the opaque disk dissipates and thins, the secondary will be much brighter at visual wavelengths than its hotter WR-like primary that will have lost its envelope, it will have substantially reduced its mass and luminosity, and it will then radiate most of its luminosity in the far-UV. Thus, when RLOF is finished and the primary finally becomes a WR-like star depleted of H, the overluminous secondary might outshine the primary at visual wavelengths. Due to the presence of recently ejected circumstellar material in a surrounding nebula, the system will continue to have bright emission lines, radio emission, and IR excess from dust. In many observable respects, the system may therefore resemble a B[e] supergiant (e.g., Zickgraf et al. 1996).

If the primary in RY Scuti is, in fact, destined to die as a Type Ib/c SN, then it provides us with a real example of what binary progenitors of SNe Ib/c may look like. Additionally, SNe I Ib are closely related to SNe Ib, except that they have a small residual H envelope; RY Scuti could therefore also die as a SN I Ib if it fails to completely shed its outer H layers before core collapse. In that case, it provides us with a Galactic analog to the progenitor of the Type I Ib explosion SN 1993J in M81 (Filippenko et al. 1994), which was inferred to be a close binary system of slightly lower initial mass that experienced an almost identical binary evolutionary path (Maund et al. 2004; see also Aldering et al. 1994; Van Dyk et al. 2002).

A distant extragalactic observer who witnesses the SN resulting from the explosion of the primary in RY Scuti might be able to infer, from appropriate pre-explosion archival data, that there was a blue star with $M_V \approx -6$ mag at the same position before the SN. This would not have been the SN progenitor itself, but the overluminous mass-gainer secondary in the close binary system. The alien observer could verify this conjecture with late-time observations showing that the blue star was not destroyed in the SN explosion. The observer might infer from single-star evolution models that this star had a ZAMS mass of $\sim 30 M_\odot$, when in fact the masses of the primary and secondary have been substantially altered by RLOF. In this case, however, it would be a mistake to disregard this surviving source as a chance coincidence, since the overluminous blue companion provides an important clue that the primary was stripped of its H envelope via RLOF in a close binary system. Indeed,

Maund et al. (2004) identified a massive blue star that might have been the surviving mass-gainer companion to the star that exploded as SN 1993J.

With only $\sim 0.003 M_\odot$ of ejected gas in the immediate circumstellar environment, the shock interaction with the surrounding torus will not be strong enough to produce a Type II_n supernova (see Smith et al. 2009). Thus, the resulting explosion from the primary in RY Scuti will likely be a Type Ib, or perhaps a Type I Ib event like SN 1993J, depending on whether all or nearly all of the H envelope is transferred from the primary to the secondary. However, an interesting consequence of the toroidal circumstellar nebula around RY Scuti is that the resulting SN might produce a strong IR echo, due to the circumstellar dust getting heated by the SN’s pulse of UV/optical luminosity.

5.3 Outbursts from the Accreting Secondary and Massive RLOF Binaries as Optical Transients

Our study provides empirical evidence that the mass-transfer phase in massive binaries can in some cases be accompanied by episodic bursts of mass ejection, rather than just a continuous and steady transfer of mass. Here we speculate about the underlying physical cause of the outbursts, and we speculate about possible observed consequences of these events.

Previous studies of RY Scuti suggest that the initially more massive star ($\sim 25 M_\odot$) has shed much of its H envelope, leaving an $8 M_\odot$ stripped-envelope star. The secondary, initially the less massive of the two, has already accreted $10\text{--}15 M_\odot$ through an accretion disk, yielding a $30 M_\odot$ star that is still largely obscured by its surrounding accretion torus. It is probable that the accreting secondary in such a system will be significantly spun up due to mass and angular momentum accretion, and may therefore be at or near critical rotation (e.g., Struve 1963; Packet 1981; Langer & Petrovich 2007; Vanbeveren et al. 1998; Langer et al. 2008). Indeed, estimates suggest that accreting even a few to 10% of a star’s mass via an accretion disk in RLOF is enough to spin up a star to near the critical rotation limit (Packet 1981; Vanbeveren et al. 1998), and this is one of the leading ideas for the formation of Be stars in binary systems (e.g., Gies 2007; Dewi 2007). The secondary star in RY Scuti has accreted a large fraction of its current stellar mass (roughly half), suggesting that it must have already encountered an angular momentum catastrophe where it has reached critical rotation, perhaps repeatedly on several occasions. Moreover, the addition of mass and heating of the envelope via accretion luminosity on a short RLOF timescale of less than 10^4 yr [shorter than the $(2\text{--}3) \times 10^4$ yr KH time of the entire star] may leave the envelope overluminous and out of thermal equilibrium with the core. Unfortunately, this is difficult to test directly, since the secondary in the RY Scuti system is hidden by an opaque accretion disk in its present state.

While in this rapidly rotating nonequilibrium configuration, the accreting secondary star may be subject to a quasi-cyclical instability whose recurrence is set by either the angular momentum diffusion timescale or the thermal timescale in the star’s outer envelope, coupled to the mass and angular momentum accretion rate. The situation is reminiscent of rotational and thermal instabilities discussed for the envelopes of LBVs (Appenzeller 1986; Stothers 2000;

Guzik et al. 1999; Davidson 1999; Smith et al. 2003). One example of these is the so-called Omega limit (Langer 1997, 1998; see also Glatzel 1998), where critical rotation combined with high luminosity leads to violent mass ejections from a massive star. Shedding mass and angular momentum in a shell ejection could temporarily alleviate the state of critical rotation — but if the angular momentum of the secondary is continually replenished with an accretion disk in RLOF, that star could repeatedly be driven to critical rotation and may therefore encounter recurring shell ejections. We suspect that this scenario might lead to repeated mass ejections like those experienced by RY Scuti. With a very high mass-transfer rate of order $10^{-3} M_{\odot} \text{ yr}^{-1}$ (i.e., $10\text{--}15 M_{\odot}$ during the RLOF phase of $\sim 10^4$ yr), the secondary of RY Scuti will accrete about $0.1 M_{\odot}$ over the observed time interval of ~ 120 yr between mass ejections. This mass gained with high specific angular momentum at the equator is more than the amount of mass lost during the same time interval, suggesting that it is enough to replenish the amount of angular momentum that was lost, and would therefore be sufficient to drive the star back to critical rotation. Further work on thermal and dynamical instabilities in the envelopes of rapidly rotating accreting secondaries in binaries would be of considerable interest. In particular, a detailed dynamical treatment of the rotating stellar envelope is needed to constrain the physics of the instability and whether it can lead to a sudden outburst. If so, it might provide a possible explanation for the origin of LBV eruptions that occur in binary systems.

Recall that our suggestion is motivated in part by the fact that invoking repeated sudden outbursts from the accreting secondary star provides a reasonable explanation for several observed properties of RY Scuti’s nebula, including its double-ring toroidal nebula, its azimuthal asymmetry, and the fact that its repeated mass ejections that occurred ~ 250 and ~ 130 yr ago both had similar geometry. The slower leaking of mass through the outer L2 point provides for equatorially enhanced mass loss, but does not seem to account for other observed properties of the system (see §5.1). In the case of RY Scuti, the amount of mass lost appears to be much smaller than the amount of mass transferred from the primary to the secondary (i.e., recent RLOF appears to be nearly conservative in the case of RY Scuti).

Sudden mass ejections are often accompanied by luminous outbursts akin to the giant eruptions observed in LBVs. There is a wide diversity of LBV-like eruptions, sometimes called “SN impostors,” which has been reviewed recently by Smith et al. (2011). The famous massive binaries η Car and HD 5980 both suffered LBV giant eruption events. There are a number of other events for which we do not know whether the progenitors are in binary systems, but two recent examples, SN 2000ch and SN 2009ip, have exhibited *repeating* LBV-like outbursts (Pastorello et al. 2010; Smith et al. 2011). Although the underlying cause of eruptions is not known, η Car exhibited brief luminous peaks in the light curve at times of periastron in the eccentric binary (Smith & Frew 2011; Smith 2011). These reached absolute magnitudes of roughly -14 mag and lasted for about 100 days, very similar to several other SN impostors. The relatively small ($0.003 M_{\odot}$) mass ejections of RY Scuti are not known to have coincided with a major brightening event, but brief outbursts in the 18th and 19th centuries might easily have

been missed if the brightening lasted only a few days. Other more extreme mass ejections in binaries are possible and do coincide with major brightening events.

We therefore speculate that some events in the population of observed extragalactic SN impostors could be related to mass ejections that are caused by an instability associated with mass and angular momentum accretion, similar to the one we outlined above for RY Scuti. Whether this is true requires more detailed theoretical study of the dynamical and thermal stability of accreting stars in RLOF. This hypothesis has the advantage that accretion-induced critical rotation can be reached for the mass gainers over a wide range in initial masses, not limited to the most massive stars near the Eddington limit. Many of the SN impostors and related transients appear to arise from stellar systems with initial masses below $20 M_{\odot}$ (see Smith et al. 2011 and references therein), and this has been difficult to understand in the context of LBV eruptions. RY Scuti presents a concrete example of a RLOF system that has experienced repeating sudden mass ejections where the mass gainer is known to be surrounded by an accretion torus.

6 CONCLUSIONS

We briefly summarise the main observational conclusions and their implications from our study of the expansion of RY Scuti’s nebula.

(1) The expansion age of the inner ionised rings measured using *HST* images indicates an ejection date of roughly 1881 (± 4 yr).

(2) The expansion age of the outer dusty IR torus measured using Keck AO images yields a likely ejection year of 1754 (± 36 yr).

(3) We therefore conclude that the two components of RY Scuti’s nebula (the inner ionised rings and the outer dust torus) were the result of two separate ejection events recurring on a timescale of $\sim 120\text{--}130$ yr. One may wonder whether RY Scuti is due for another such ejection event in the near future.

(4) Conclusion (3) is supported by a clear spatial gap between the two structural components, indicating that they are not interacting hydrodynamically. Therefore, one cannot invoke a distant pre-existing disk as the shaping mechanism for the double-ring nebula. This gap also indicates that few ionising photons can penetrate the inner ionised rings. We speculate that the second ejection event, which is now seen as the expanding ionised rings in *HST* images, may have shielded the outer torus from the stars’ ionising radiation, thereby allowing dust to form in the outer torus.

(5) We suggest a formation mechanism for the toroidal circumstellar nebula that involves matter ejected suddenly (i.e., dynamically) by the accreting secondary star, and immediately being shaped by the opaque accretion torus that is thought to surround the secondary star, although we encourage numerical simulations of this scenario.

(6) The primary star in RY Scuti, which is in the process of losing its H envelope via RLOF, is our best-studied candidate for the progenitor of a Type IIb or Type Ibc supernova where the envelope stripping from close binary evolution is currently underway. While other post-RLOF systems are good candidates for SNe Ibc as well, RY Scuti is a rare

example of a system that is currently in the critical mass transfer phase, and which is surrounded by a nebula that allows us to measure the mass lost from the system.

(7) RY Scuti suggests, therefore, that the formation of SN Ibc progenitors via RLOF may in some cases be punctuated by sudden, repeating episodes of mass loss. We speculate that this may be the result of an instability associated with mass and angular momentum accretion by the secondary star, although this idea deserves additional study. In some cases these mass-ejection events may be seen as luminous outbursts, even though we are aware of no such record of an observed outburst in the specific case of RY Scuti. It is worth considering the possibility that other close binary systems may contribute to the diverse population of non-supernova optical transients now being discovered.

(8) When RLOF finishes for RY Scuti, we speculate that the accretion torus around the secondary will become optically thin, revealing the rapidly rotating and overluminous mass gainer. The system will also be surrounded by a dusty torus resembling those seen in B[e] stars. If this overluminous 30 M_{\odot} secondary star dominates the optical luminosity of the system, it may point toward an observed association between OB emission-line stars and some SN Ibc progenitors, even though it is the companion to the overluminous OB star that actually explodes.

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